Abrasion experiments of mineral and meteorite grains: Application to grain abrasion of Itokawa, Ryugu and lunar regolith particles.

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Introduction: The external 3D shapes of Itokawa regolith particles by X-ray microtomography showed that some particles have rounded edges, which should be formed by mechanical abrasion [1]. Abraded surfaces were confirmed by detailed observation using SEM [2]. Mechanical abrasion of lunar regolith particles was also recognized by X-ray microtomography and SEM as well [3]. Seismic wave induced by micrometeoroid impacts [1], YORP effect and tidal motion [4] were proposed for the abrasion process on Itokawa.

In order to understand detailed process of the abrasion, abrasion experiments have been carried out [5]. In these abrasion experiments, quartz, olivine ($Fo_{\sim 90}$ from San Carlos), corundum and calcite (marble) as mineral samples and Sayh al Uhaymir 001 (L5) and Murchison (CM2) as meteorite samples were used. They were crushed into particles 1-2 mm in size except for corundum (~1mm). These particles (~6.5g) were put into a vessel (10 mL) (filling fraction of 50%) without any crushing tool, and the vessel was vibrated in a mill (Multi-beads-shocker: YASUIKIKAI Co.). Time changes of the amounts of powders produced by abrasion and their external shapes using X-ray microtomography were measured. In addition, the external shapes of marked particles were traced using X-ray nanotomography in a series of abrasion experiments. Based on the experiments, two modes of abrasion were recognized; gradual wearing and chipping of particle edges. The 3-axial ratios of particles almost unchanged by gradual wearing while they changed by chipping. It was proposed that the former process is responsible for Itokawa particle abrasion and later for lunar particle abrasion. However, the grain size used in the experiments (~1 mm) is larger than the regolith particle size (~0.1 mm).

In this study, additional experiments were made to understand the size effect and the abrasion rates were applied to abrasion on Itokawa and Moon by considering the size effect. Abrasion of Ryugu regolith particles, which will be returned by the Hayabusa2 spacecraft, was also discussed.

Experiments and analytical procedure: Quartz particles with three different sizes (0.5-1 mm, 1-2 mm and 2-4 mm) were used in the experiments on the size effect. The abrasion experiments were made at vibration rate of 2000 rpm only for 1 min. The other conditions are the same as those in the previous experiments. After the experiments, the mass of powder (<250 μm) produced by abrasion was measured.

Figure 1 shows the result in the previous experiments using olivine grains [5], where proportion of abraded powder in the total mass as the amount of abrasion, P, is plotted against the duration, t. We used the proportion at first 1 min., P_1, as the representative of the abrasion rate for comparison among different samples and sizes.

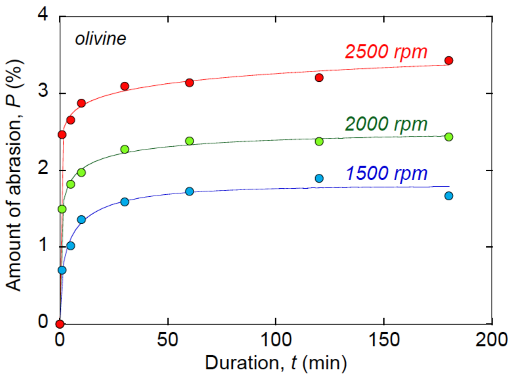

Figure 1. Amount of abrasion, P, plotted against duration, t, for different vibration rates, ω, using olivine samples.

Results: In the present experiments, the P_1 value is almost proportional to the average of particles size, d; P_1 (%) = 0.849(12) × $d^{0.987(15)}$ (Fig. 2). By using this relation, we can correct P_1 values of a different size to that of 1-2 mm particle. Figure 3 shows the P_1 values for different samples with 1-2 mm as a function of the vibration rates, ω. P_1 increases with increasing ω in a power law with the power index of ~2 to 3. These relations may correspond to $E_{vib} \propto \omega^2$, where E is the vibration energy. The abrasion rate decreases from corundum, olivine ~

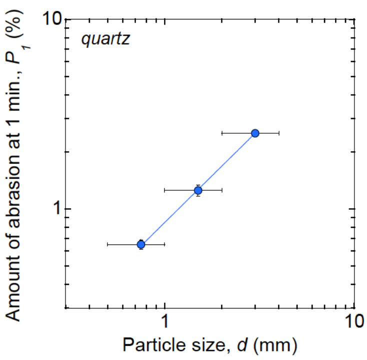

Figure 2. Amount of abrasion at 1 min., P_1, plotted against particle size, d, of quartz at ω =2000 rpm.

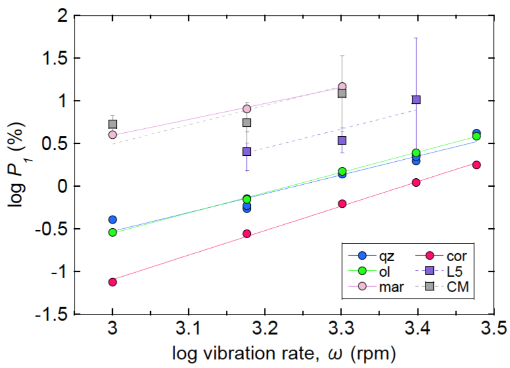

Figure 3. Amount of abrasion at 1 min., P_1, for 1-2 mm grains plotted against vibration rates, ω.

quartz to calcite (marble), and this order is consistent with their mechanical strengths. The data of L5 and CM chondrites were obtained from only six particles in each run and thus have large errors.

Discussion: The degrees of abrasion of regolith particles on Itokawa and Moon were roughly estimated from the present experiments. Figure 4 shows P_1 in a wide range of ω, where the values of P_1 of SaU 001 (L5) and Murchison (CM) grains obtained in the experiments are extrapolated with the log slop of 2 by considering $E_{vib} \propto \omega^2$. The following three types of estimation were made; (1) abrasion by impact-induced convection in a regolith layer, (2) abrasion in an ejecta during impact and (3) abrasion in a regolith layer during impact. In order to compare the grain velocity, v, and acceleration, a, in the models with those of the experiments, we used the means of absolute velocity and acceleration (<|v|> and <|a|>, respectively) by assuming simple harmonic motion of the sample vessel in the experiments (amplitude; 0.015 m). The corresponding values of <|v|> and <|a|> to ω are shown in Figure 4.

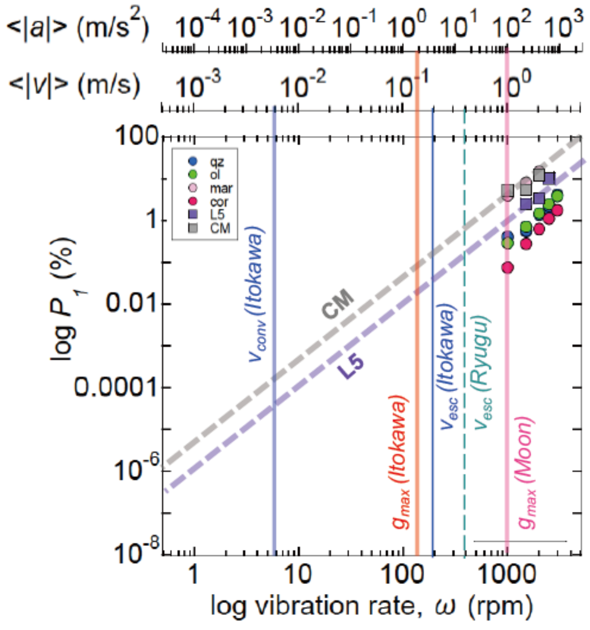

Figure 4. Estimation of the amount of abrasion at 1 min., P_1, with 1-2 mm grains for Itokawa, Ryugu and Moon.

(1) *Abrasion by impact-induced convection*: Yamada and Katsuragi [6] estimated the convection velocity, v_{cov}, in a regolith layer of Itokawa due to impact-induced seismic shaking [1]. The typical value at the time of impact is ~6 mm/s. The corresponding P_1 for L5 is only 10^{-4}~10^{-5} %, and if the size effect ($P_1 \propto d^{-1}$) is taken into consideration P_1 with a few 100 μm grains should be 10^{-4}~10^{-5} %. These values indicate that abrasion cannot effectively occur by this process on Itokawa.

(2) *Abrasion in an ejecta during impact*: In order to evaluate the possibility of abrasion by contact of grains during excavation and ejection by impact, the ejecta velocity, v_{eject}, was estimated as a function of the launch position of ejecta from the crater center, x, and the crater radius, R, using the model of [7]. On Itokawa, v_{eject} ~0.001–0.1 m/s (corresponding ω~1–100 rpm) for R=1 cm–100 m at x/R~1. The corresponding P_1 values for 1-2 mm L5 grains are ~0.01– ~10^{-6} % (Fig. 4) (~0.001– ~10^{-7} % for a few 100's μm grains). This indicates that effective abrasion is not expected. It should be also noted that only grains with v_{eject} less than the escape velocity of Itokawa, v_{esc}~0.2 m/s, can survive, suggesting P_1<~0.01 % for 1-2mm grains (Fig.4). In contrast, on Moon, v_{eject} > 1 m/s (ω>~1000 rpm) for R>1 m at x/R~1, indicating that abrasion is possible on Moon by this mechanism.

(3) *Abrasion in a regolith layer during impact*: In order to evaluate the possibility of abrasion by contact of grains in a regolith layer during impact, the maximum acceleration of the first peak on impact-induced seismic wave, g_{max}, was estimated as a function of distance from the impact point, x, for different impactor radius, r, using the model of [8] and the crater size model using the π-scaling theory [9]. The estimated g_{max} values on Itokawa and Moon are ~2 and ~100 m/s^2 irrespective of the impact conditions. The corresponding P_1 values for 1-2 mm L5 grains are ~0.01 and ~1 % (~0.001 and ~0.1 % for a few 100's μm grains) on Itokawa and Moon, respectively (Fig. 4). Therefore, abrasion on Itokawa is not possible while it is possible on Moon.

The above discussion suggests that abrasion by impact is almost impossible on Itokawa while it is possible on Moon. Mechanical abrasion is so high energetic process that this cannot occur on small asteroids, like Itokawa. Accordingly, Itokawa regolith particles with rounded surfaces by abrasion should originate from the parental body of Itokawa, where abrasion occurred by impact on the body. For the case of Ryugu, v_{conv} may be also small and thus abrasion is not expected even for materials with smaller strength, like CM, by the process (1). In the process (2), if v_{eject} is slightly less than v_{esc} (~0.4 m/s), the maximum values of P_1 for CM grains are estimated to be ~1 % (1-2 mm) and ~0.1 % (a few100's μm) (Fig.4). Similar values of P_1 are expected in the process of (3) although we cannot estimate g_{max} with good precision at this moment. These P_1 values may suggest that a small degree of abrasion of regolith particles on Ryugu is possible.

References: [1] Tsuchiyama A. et al. 2011. Science, 333: 1121. [2] Matsumoto T. et al. 2016. GCA 187: 195. [3] Tsuchiyama A. et al. 2016. 4th Symp. Solar System Materials. [4] Connolly H. et al. 2015. EPS 67: 12. [5] Tsuchiyama A. et al. 2018. Abstract #1844. 49nd LPSC. [6] Yamada T. M. and Katsuragi H. 2016. Planetary and Space Science 100: 79. [7] Housen & Holsapple, 2011. [8] Yasui, M. et al. 2015, Icarus 260: 320. [9] Holsapple, K. A. 1993. Annu. Rev. Earth Planet. Sci. 21: 333.